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Experimental comparison of two linear machines developed for the free piston engine

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Abstract

In this paper, a linear synchronous machine is compared with a linear transverse flux machine. Both machines have been designed and built with the intention of being used as the power take off in a free piston engine. As both topologies are cylindrical, it is not possible to construct either using just flat laminations and so alternative methods are described and demonstrated. Despite the difference in topology and specification, the machines are compared on a common base in terms of rated force and suitability for use as a generator. Experience gained during the manufacture of two prototypes is described.

1 Introduction

A direct drive free piston engine is a combustion engine where reciprocating pistons are used to drive an electrical generator. It is hoped that the elimination of the rotary part of the engine will result in a low mass, low loss electrical generator, for use as a range extender in electric vehicles for example. The movement of a free piston engine is linear, with a peak to peak amplitude of perhaps 0.2 m and a mechanical frequency of the order of 20Hz. The success of the concept relies on development and demonstration of the thermodynamic cycle and small linear electrical machines.

A number of studies have been carried out by this [1-3] and other authors [4] on the machine topologies suitable for this application. Most of the work on the generator comes from a machine design perspective, focusing on electro-magnetic analytical and finite element work. Integration of the machine into a range extender also requires mechanical and electrical integration aspects to be considered. Figure 1 shows a concept presently being developed at Newcastle University.

This paper reports on the experimental demonstration of two electrical machines designed for this application: a tubular permanent magnet machine referred to as the Linear Synchronous Machine (LSM) and a modulated pole Transverse Flux Machine (TFM). Both machines have a cylindrical cross section and involve magnets mounted on a moving translator. Both machines have unusual construction and rely on three dimensional flux paths guided by soft magnetic composites. The same test facilities have been used to evaluate both topologies.

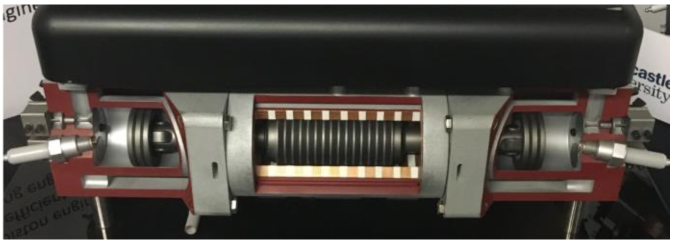

Figure 1: Model of an integrated free piston engine

2 Linear Machines

For this study two permanent magnet linear cylindrical machines have been selected - which in some respects represent the two extremes of machine design. The LSM is a surface mounted PM machine, which is a conceptually simple topology, analogous to the surface mounted rotary synchronous PM machine, known for high overload torque density and relatively straightforward construction. The TFM, on the other hand, in its rotary form requires unconventional construction [5], is known for effective use of PM material, has good rated performance but is less good in extreme overload conditions [6].

Assuming that integration into a free piston engine requires a cylindrical or tubular construction, neither of these linear machines can be made from conventional lamination stacks, and so arguments about construction of the rotary counterpart are less relevant.

3 Specification

The LSM was designed for use with an external combustion free piston engine, based on [7], requiring a rated force capability of 800 N and connected to a resistive load. The TFM was designed for an internal combustion free piston engine described in [8], has a rated force of 1500 N and assumes a fully rated inverter as a load. Table 1 shows the machine specifications.

	TFM	LSM
Rated Force (N)	1500	800
Stroke (mm)	152.4	120
Machine Active Length (mm)	150	120
Active Length/Stroke Length	1	1
Airgap (mm)	1	1.5
peak speed (m/s)	2.54	4.8
Translator Mass (Kg)	≤6	≤6

Table 1: Target specification for two machines

4 Linear Synchronous Machine

4.1 Topology Description

The LSM is a cylindrical surface mounted PM machine, a section of which is shown in Figure 2. At the design stage, radial, axial and Halbach permanent magnets were considered within the volumetric constraints of the system [1]. The radial machine was found not to reach the design force and so was discounted. The remaining topologies were evaluated using a weighted function of the form given in (1), where the base value was that of the lowest magnet mass machine. The three coefficients for assessment were magnet mass, moving mass and overall machine efficiency. The parameters are compared in Figure 3, where for the constraints given in Table 1, axially magnetised magnets offered the best overall machine.

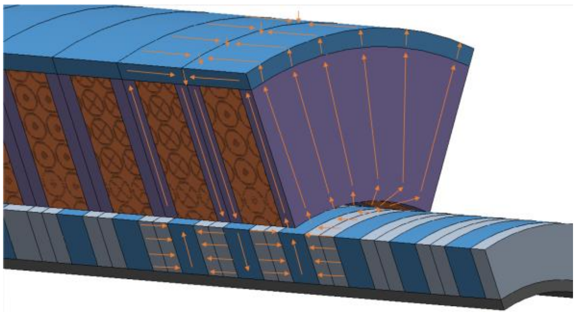

Figure 2: The LSM

$$\%\,Coeffcient_{1,2} = \left(1 - \frac{Coeffcient\ value_{1,2} - Base}{Coeffcient\ value_{1,2}}\right) \times X_{1,2}\% \quad (1)$$

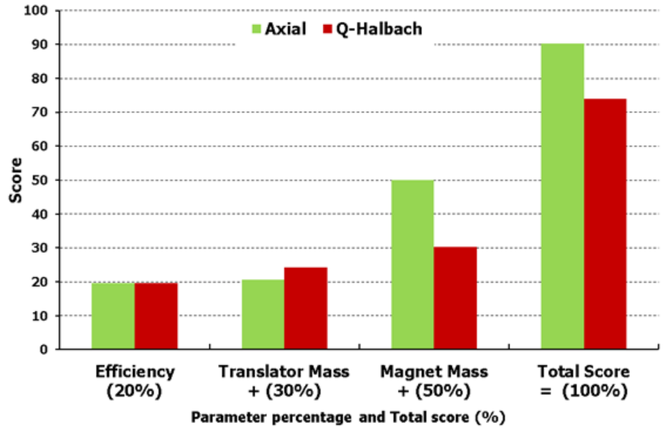

Figure 3: Selection of magnet orientation for the LSM

4.2 Build and Test

The translator has an axisymmetric flux path and employs flux concentration in the axial radial plane. Whilst in theory this could be hosted by radially laminated pole pieces, this was unlikely to be practical to build. Similarly solid electrical steel would have given high losses and so Soft Magnetic Composite (SMC) blocks were used. These were mounted on a central non-magnetic support tube.

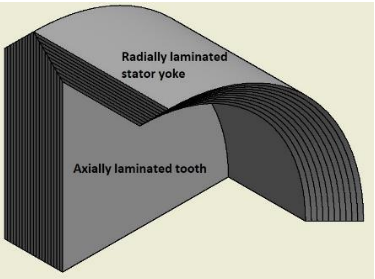

Figure 4: Laminated stator concept

For the stator teeth, flux flow is radial and perhaps axial, and for the stator coreback, flux flow is axial and radial. The entire stator could have been SMC, although as the prototype material is supplied in 200 mm billets construction would have been challenging. Similarly, a radially laminated core back interfacing with axially laminated teeth could have been used, Figure 4, although experience of radial laminations is limited. The stator was made from axially laminated teeth stacked to form rings, interfaced into an SMC coreback made from segments, Figure 5.

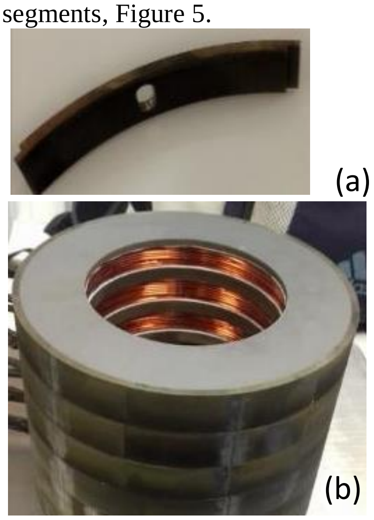

Figure 5: (a) individual smc coreback segment (b) assembled SMC coreback and laminated teeth

The stator was mounted within an aluminium housing and the translator on a stainless rod supported by solid bearings, Figure 6.

A ball screw was used to drive the machine to obtain open circuit emf and static torque capability. In both cases the results, shown in Figure 7 and 8, validate the FEA.

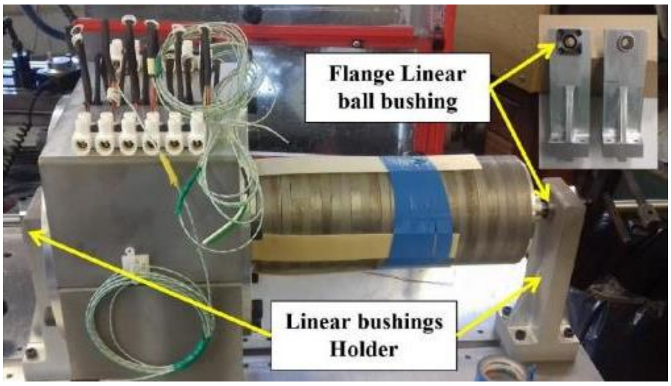

Figure 6: Translator during insertion into the stator

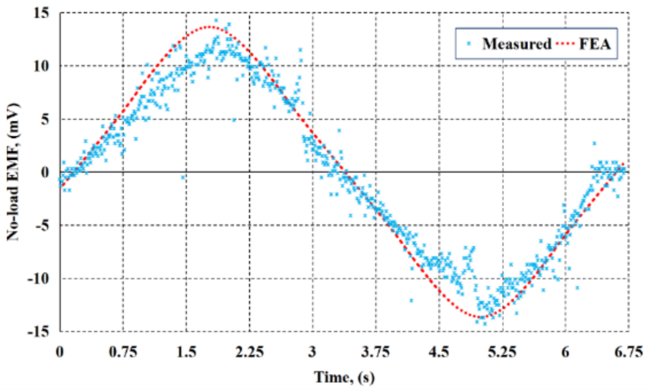

Figure 7: Open circuit back emf for the LSM when driven at constant speed

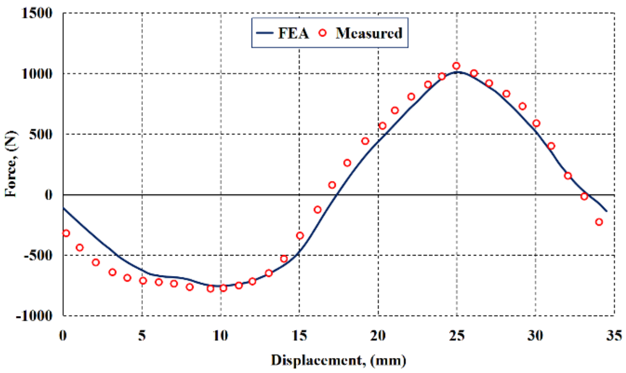

Figure 8: Static force capability verses translator position for a constant DC current

5 Linear Transverse Flux Machine

5.1 Topology description

Figure 9 shows a single phase of a linear TFM with axially magnetized permanent magnets on the translator [9]. Within the translator, magnetic flux travels axially from the magnet into the pole pieces (1), radially across the air gap and into the stator tooth (2). It is a similar construction to that used in the LSM.

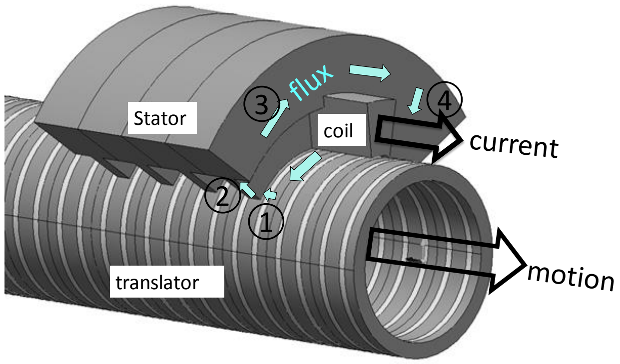

Figure 9: TFM flux schematic diagram

In the stator core back, flux travel is axial and circumferential around the outer edge of the coil (3) to align with the next translator pole piece. The path is completed by radially returning down a stator tooth (4), across the air gap into the translator pole piece.

As these machines have an inherently low reluctance, they tend to be quite force dense and so optimising the design for low magnet mass is relatively straightforward. However, this naturally leads to machines with a high inductance and low power factor. For practical use as a generator, it is better to look at machines with a higher magnet mass, but a corresponding lower electric loading and better power factor [10].

5.2 Building and test

As with the LSM, the magnetic poles of the translator could only really be made from SMC. The stator has an inherently three dimensional flux path, and so cannot be made from a simple single laminated structure. To demonstrate an alternative to SMC as a coreback material, a concept was devised whereby the teeth where made from axially laminated laminations and they were magnetically connected via radially laminated blocks, Figure 10. The blocks are held in place by a non-magnetic (composite) structure. The construction of this machine is fully described in [11]. The assembled machine was driven by a ball screw, Figure 11, and the results used to validate back emf predictions, as shown in Figure 12.

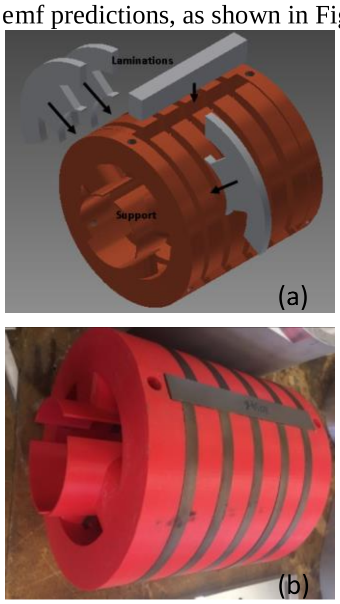

Figure 10: TFM stator construction (a) concept (b) prototype

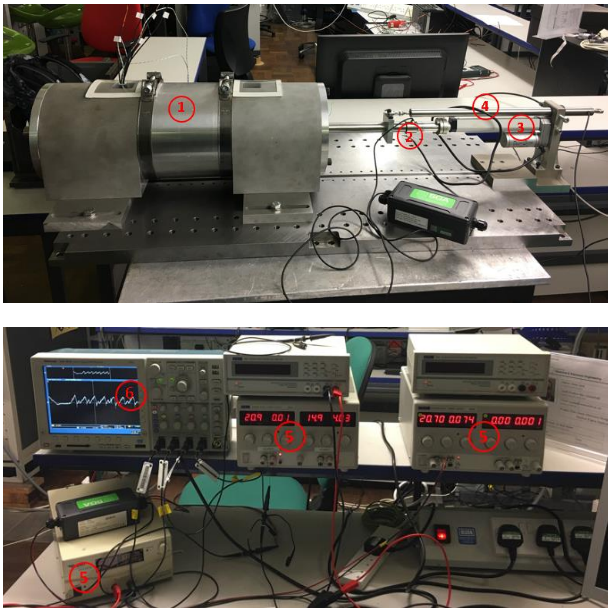

Figure 11: Test- rig used for both machines: 1 TFM; 2 load cell; 3 linear actuator; 4 displacement transducer; 5 DC power source; 6 oscilloscope

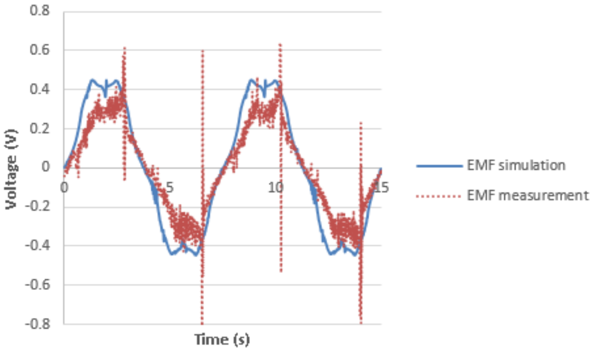

Figure 12: Example of back emf result used to validate TFM FEA

6 Comparison

6.1 Physical

Table 2 shows a summary of the parameters of the two designed machines. Most notably, the TFM has a rated force of double that of the LSM, despite the fact the LSM was designed to have twice the current density. As magnet mass was unconstrained in this study, this is perhaps not a fair comparison.

	TFM	LSM
Number of turns	120	40
Translator Poles	20	14
PM Mass (kg)	2.33	1.59
Stator Mass (kg)	13.8	16.45
Translator mass (kg)	5.96	7.4
PM Material	NdFeB: Neodymium Iron Boron	SmC017
Electrical Power Output (kW)	3.8	3.83
Efficiency (%)	97	94.6
Power Factor	0.62	0.7

Jmax (A/mm^2)	3.5	6.0
Total Mass (kg)	24	20
Shaft Diameter (mm)	25	12

Table 2: Parameters of compared machines

Figure 13 compares the machines at rated current density where most parameters of the LSM are used as the base for a per unit comparison of the two machines. Efficiency and power factor are not scaled. In terms of absolute force, force per unit mass and efficiency, the TFM is the stronger machine.

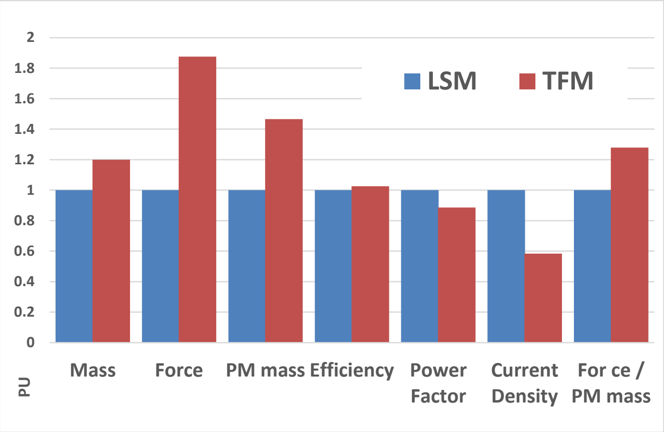

Figure 13: Per unit comparison. Mass, magnet mass, current density and force per kg magnet mass all use a per unit base of the LSM values. Efficiency and power factor are the absolute values.

Neither the power converter kVA rating nor the current density is equal in these designs. The LSM was designed to feed a simple resistive load, with the TFM coupled to a fully controlled converter. The direct comparison of Table 2 must therefore be treated with caution.

6.2 Machine constant density

The different specification and different current density used in the design studies skews the comparison as force capability, efficiency and mass are all relevant. Considering just copper losses, which will be dominant at rated force, the Machine Constant (*MC*) for an *m* phase machine can be defined it terms of its force *F*, rms current I_{rms} and phase resistance *R* as in Equation (2).

$$MC = \frac{F}{\sqrt{mRI_{rms}^2}} \qquad (2)$$

In terms of mass or volume *V*, the Machine Constant Density *MCD* can be defined as in Equation (3).

$$MCD = \frac{MC}{V} = \frac{F}{V * \sqrt{mRI_{rms}^2}} \qquad (3)$$

Table 3 shows the *MCD* for the two machines, where once more the TFM appears to be the stronger machine.

	MCD (kN/ (kg √W))
LSM	21
TFM	59

Table 3: Machine constant density comparison

6.3 Electrical

Near rated current, both machines can be represented by an equivalent circuit consisting of an emf, a series resistance and a series reactance. Table 4 shows the component values for the two machines, based on finite element analysis predictions.

		LSM	TFM
Turns per phase		40	120

Peak flux	Wb	0.0031	0.00063
Inductance	H	0.0027	0.045
Resistance	Ohm	0.227	1.42
Peak electrical frequency	Hz	130	146

Table 4: Equivalent circuit parameters

When coupled to a free piston engine, the excitation velocity of the electrical machines will be almost sinusoidal. Assuming a peak speed of 4.6 m/s, the predicted open circuit emf of the two machines is shown in Figure 14.

When coupled to a simple resistive load, the RMS power developed in the load is dictated by the value of that resistance. For example, Figure 15 shows the characteristics of the LSM over a range of loads. The RMS power is seen to be a maximum of over 2kW at around 2 Ohms, which corresponds well to the impedance calculated using the values in Table 4.

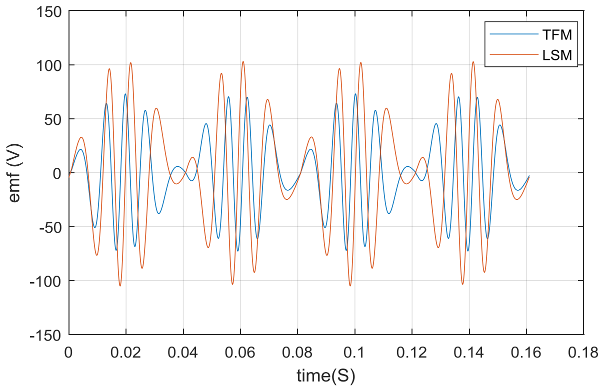

Figure 14: back emf of machines coupled to a sine wave

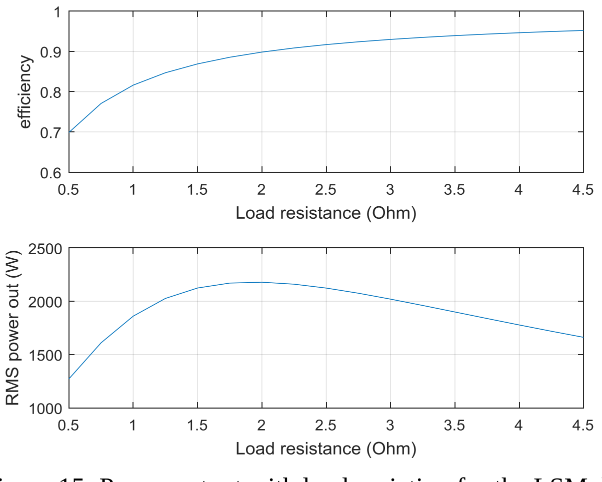

Figure 15: Power output with load variation for the LSM driven at a near sinusoidal wave form with peak speed 4.6 m/s

For the TFM, the increased frequency, resistance and most importantly inductance results in a maximum power transfer occurring at a load resistance of around 40 Ohms, with a real power output just a fraction of that from the LSM. The inductance prevents the machine extracting any real power, making this machine almost useless without a fully rated inverter at its output as capacitive tuning is not possible in this variable frequency application.

The power output of the TFM is much lower than the power factor of 0.62 would imply. There are lessons to be learnt here about designing a generator as a motor with a constant current density in FEA. Furthermore, as this was mainly an electrical topology demonstration project, the authors were more concerned with fill factor than turn number [11]. Assuming a reduction in turn number gives a linear reduction in emf and resistance, and a square reduction in inductance, the equivalent circuit model implies the power could be increased slightly, but will always be well below the LSM.

6.4 Mechanical

In a cylindrical linear machine with moving magnets, it is hard to envisage a translator that does not require SMC. On this basis, the translator of the LSM and TFM are mechanically equivalent.

In terms of the stator, the mechanical structures are quite different and experience gained is worth sharing. In rotary machines, the TFM can justifiably be called hard to manufacture, and often the 3D flux path forces the machine to be fabricated from SMC or bent laminations [12]. In this study, however, it is the LSM that has SMC in the stator and the transverse flux machine has a purely laminated structure.

For prototype machines, it is not normally feasible to construct large SMC corebacks as a single pressed component, as might be expected in a production machine. Instead, mechanically robust prototype grade SMC can be supplied in cylindrical billets. These must then be machined into intersecting segments to make larger components. Although cutting tolerances can be tightly controlled, stack tolerance is still a concern and airgaps are inevitable.

Both stators include laminations that must be magnetically coupled: to other laminations in the TFM and to SMC in the LSM. In the TFM, the stator consists of relatively fewer components and so overall fittings are likely to be better. Hence the normal arguments about fabrication based on production experience of rotary machines are not necessarily applicable to prototype linear machines.

7 Conclusion

Two cylindrical machines have been introduced. Whilst the per unit force performance of the transverse flux machine was significantly better than the synchronous machine in the design study, its performance when coupled to a resistive load was significantly poorer.

The build of both machines is discussed and it is argued that aversion to 3D flux topologies in rotary machines should not influence design decisions about tubular linear machines.

References.

[1] A Sa Jalal, N J Baker and D Wu, "Design of tubular Moving Magnet Linear Alternator for use with an External Combustion – Free Piston Engine", *IET Pwr Elect. Machines and Drives* (PEMD). Glasgow 2016

[2] A Sa Jalal, N J Baker and D Wu, "Electrical Machine Design for use in an External Combustion Free Piston Engine", *IET Ren. Pwr Gen Conf.* RPG 2016

[3] Wang J, Baker N, "Comparison of flux switching and modulated pole linear machines for use with a free piston", *IEEE Elec. Mch & Dr Conf* (IEMDC), 2015,

[4] J. Wang, M. West, D. Howe, H. Zelaya-De La Parra and W. M. Arshad, "Design and Experimental Verification of a Linear Permanent Magnet Generator for a Free Piston Energy Converter," *IEEE Trans. Engy Conv* , Vol. 22, No.2, pp. 299-306, 2007.

[5] S. Jordan and N. Baker, "Comparison of Two Transverse Flux Machines for an Aerospace Application" IEEE Int Electric Machines and Drives Conf (IEMDC). 2017, Miami, FL, USA

[6] I. Martinez-Ocaña, N. J. Baker, B. C. Mecrow, C. Hilton, S. Brockway, Transverse Flux Machines as an alternative to Radial Flux Machines in an in-wheel motor", *IET Pwr Elect. Machines and Drives* (PEMD), 2018l Liverpool (submitted).

[7] D. Wu and A. P. Roskilly, "Design and Parametric Analysis of Linear Joule-cycle Engine with Out-of-cylinder Combustion," *Energy Procedia*, vol. 61, no. Supplement C, pp. 1111-1114, .

[8] R. Mikalsen and A. P. Roskilly, "The design and simulation of a two-stroke free-piston compression ignition engine for electrical power generation," *App. Therm. Engn*, vol. 28, no. 5, pp. 589-600

[9] Wang, J. and Baker, N.J., 2015, May. Comparison of flux switching and modulated pole linear machines for use with a free piston. In Electric Machines & Drives Conference (IEMDC), 2015 IEEE International (pp. 642-648). IEEE.

[10] Baker, N.J., Wang, J. and Atkinson, G.J., 2016, September. Optimization and comparison of linear transverse flux and flux switching machines. *Int. Conf on Elec Mchn* (ICEM), 2016 XXII (pp. 2471-2477). IEEE.

[11] Wang J., Baker N.B., Gavrilov B "A study of the assembly, build and test of a linear transverse flux machine", *IET Pwr Elect. Machines and Drives* (PEMD), 2018l Liverpool (submitted)

[12] S. Jordan, N.J. Baker, J.G. Washington, G.J. Atkinson and E. Pinguey, "Construction Methods for Modulated Pole Machines", IEEE Int. Electric Machines and Drives Conf (IEMDC). 2017, Miami, FL, USA